“METAL CASTING INNOVATIONS, 1952-2012 AND BEYOND... A PERSONAL VIEW”

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Introduction

I am very happy to be present at this 60th anniversary of the founding of the Institute of Indian Foundrymen, and to discuss some of the important innovations in our industry that have occurred over this time. My own career in the foundry industry coincides almost exactly with the 60 years your Institute has been in existence, and I trust therefore that the audience will forgive me if I interweave some of my own experiences, and those of my students, with this summary of metal casting innovations.

Innovation is the complex process of introducing novel ideas, usually inventions, into use and includes entrepreneurship as an integral part. *Invention* is the process of devising and producing by independent investigation, experimentation and mental activity something that is useful and not previously existing. Inventions are often divided into two categories: macro and micro. *Macro-inventions* are inventions of sufficient import that they change a field in significant ways and spawn many improvements: *micro-inventions*.

Two of the metal casting processes that I will discuss in this lecture clearly qualify as macro-inventions. These are ductile iron casting and shell investment casting. These original inventions have spawned large numbers of micro-inventions and led to the development of major industries; they have spawned multi-billion dollar industries. In short, they have led to major innovations in the casting field. Of the innumerable micro-inventions in our field over these past decades, some are of considerable industrial importance and others are practiced today only to limited extent, but, may someday occupy a more prominent role in our industry.

Ductile Iron Castings

Cast iron has been an important engineering material in the east for two thousand years, and in the west for 500 years. Over these years, many methods have been developed for modifying the internal structure of cast iron, but none of these were more important than the discovery a little more than 60 years ago that the as-cast structure could be altered from a flake morphology to a spherical morphology, Figure 1.

The original announcement that such a structure change could be made came from Henton Morrogh of the BCIRA in 1946. His process involved cerium inoculation of the melt. He presented his work to the AFS in Philadelphia in 1948, and at that meeting Keith Millis of International Nickel Company, announced that magnesium inoculation similarly modified the melt. That 1948 meeting was a time of high excitement. The ability to change the graphite morphology so remarkably from flakes to spheres, meant the invention of a radically new engineering material with vastly improved performance in many applications.

Toyota Professor MIT, USA

The year after that conference, in 1949, while I was still an undergraduate, the first ductile iron conference was held at MIT, under the leadership of the then foundry professor, Howard F. Taylor. It was widely attended by foundrymen and paved the way for rapid acceptance of the process by American industry. Production of ductile iron rocker arms commenced at Ford the following year.

Maurice Grandpierre, the son of the then-Director General of Pont à Mousson foundry in Nancy France was a graduate student in the Metallurgy Department of MIT at that time. When he graduated, in 1950, he returned to Nancy with a ductile iron license from INCO in hand. With Maurice's leadership, Pont à Mousson led the way internationally in introducing ductile iron pipe to the marketplace. Ductile iron pipe proved so superior to gray iron pipe that it soon became the dominant cast pipe material worldwide and today accounts for the largest art of the annual production of ductile cast iron.

In the US, production of ductile iron grew slowly at first, reaching only 100,000 tons annually in 1958, but this was soon to change and by the mid-1960's it had reached 2 million tons and today stands at about 4 million tons, Figure 2. Worldwide production today is about 20 million tons. During that same period, US production of gray iron decreased from about 14 million tons to about that of ductile iron today: 4 million tons.

This rapid growth of ductile production has been due to gradual and accelerating market acceptance of the material, greatly aided by the many micro-inventions over the years that have improved the process and the product.

Lost Foam Casting

In early 1956, after I returned to MIT to join the metallurgy faculty, I was asked to visit the workshop of a local artist who was practicing a rudimentary form of what we now term "Lost Foam Casting". The process employs a foam polymer pattern that is removed from the mold only by the heat of the metal as it enters into the mold. The process was intriguing to us and we obtained funds to work with the artist, Alfred Duca, to develop it into a practical method for the casting of art. At that time we had quite a large foundry laboratory and could make quite substantial test castings.The following several figures show steps in the casting of one of these: a bronze "Pegasus," The artist first carved Pegasus from foam polystyrene, Figure 3. We then coated it, hollowed it out, molded it in sand, and poured metal into a styrofoam sprue. Figure 4 shows Pegasus as he emerged from the mold, and Figure 5 is the finished sculpture.

In the years to follow, the process gradually found industrial applications, first as patterns for blind risers in ferrous sand castings and then as patterns for complete castings, especially aluminum castings. Today, there exists a substantial worldwide production of aluminum components by the process, including engine blocks such as the one shown, along with its foam polystyrene pattern, in Figure 6.

Premium Quality Aluminum Castings

During the 1950's and 1960's we had strong support in the MIT foundry laboratory from the Department of Defense for research to improve the properties and reliability of aluminum castings. We first built on the work of others to demonstrate the importance of purity, cleanliness, degassing, gentle mold filling, heat treatment control and grain refinement. We soon found, however, that when all these variables were well controlled, there was another, vitally important factor: "dendrite arm spacing," the internal fine structure with the grains, Figure 7. We then went on to show that for fundamental reasons, there is only one way to control the dendrite arm spacing: by controlling cooling rate. The faster a casting is cooled during solidification, the finer the dendrite arm spacing and, the stronger, more ductile the casting, providing, of course, the casting is sound and free from other defects.

The technique used industrially to achieve this rapid cooling, while also achieving good directional solidification, is to use employ a metal/sand mold composite. This may be done by selectively placing chills in complex sand molds or by using molds having the drag half a metal mold, directing solidification upward. I spent a few years in industry in the mid-1950's developing practical techniques for producing these castings and developing the data to form the basis of the early specifications for them. Figure 8 shows an example of chill placement in the drag of one of the castings we produced in those days. Note the each of the chills is placed so as to achieve directional solidification toward a chill. Figure 9 is the finished casting. A government specification (QQA-601) for these "Premium Quality Castings" was issued by the end of the '50's and ASTM standards followed, the current one being ASTM B686/B686M.

The specifications, modified over the years, continue to be the basis of a thriving segment of the aluminum casting industry. A modern application of the principles of premium quality casting technology to a high production process is the method being introduced by General Motors for engine blocks and other parts. The critical solidification control is obtained by heavy chilling with directional solidification toward risers, through use of a combined metal/sand mold. Figure 10 shows the coated heavy metal chill at the base of the casting. The main sand core is shown in Figure 11,and placement of the core package in Figure 12.

The mold is inverted before casting, and metal filled electromagnetically, at carefully controlled velocities, into what is then the bottom, through the risers. After filling, the mold is re-inverted so the last metal in (at the risers) is now at the top of the mold. Figure 13 shows withdrawal of the casting from the mold. Mechanical properties, soundness and cleanliness in complex aluminum castings obtained by this process are unexcelled by any other engine block casting process today.

The semi-permanent casting process is also being used in the manufacture of cylinder heads. The method used to produce these heads involves metal tooling to form most of the exterior features of the head with sand cores to form the internal cavities. The metal mold is coated with a ceramic based coating to control heat transfer across the surface. Water cooling can be directed to certain areas of the casting to provide even faster solidification than can be achieved in a regular metal mold, thus providing even finer dendrite arm spacing and better mechanical properties. Metal can be introduced into the mold in a variety of ways including gravity fill from a ladle, low pressure fill from a furnace or tilting into the cavity from a basin.

Investment Casting

Investment casting, like cast iron, has a long and illustrious history, originally used primarily for jewelry and dentistry. The process employed consisted of a surrounding a wax pattern with a ceramic slurry confined in a metal flask, thus producing a "solid mold." In the mid-to-late 1940's this solid mold process was adapted for production of turbine blades for the then nascent jet engine industry.

The solid mold process, however, was costly in terms of amount of refractory required and it required long heating times to burn out the wax. It was soon found to be inadequate for producing large molds of multiple complex castings. These problems were solved by the invention in the 1950's of the ceramic shell mold, an invention that was to be critical to the subsequent growth of the industry to the multibillion dollar industry it is today. The shell ceramic process uses far less mold material, can be heated much more quickly, and can produce much larger complex castings than the older solid mold process.

Today, investment castings comprise a $10 billion market worldwide, Figure 14. The North American share is $4 billion, Asian $3.6 billion, and European $2.4 billion. Three fourths of the North American share is aircraft and industrial gas turbine, Figure 15. Superalloys and steel comprise the bulk of the castings produced, the remainder being primarily titanium, aluminum and copper, Figure 16.

The invention of the shell ceramic mold has spawned many mini-inventions, some of them not so mini any more. The thin mold made possible the independent control of thermal gradient and isotherm velocity, leading to the development of the "directionally solidified" and "single crystal" casting processes, Figure 17. Because of their superior high temperature performance, these castings have become ubiquitous for aircraft turbines and are achieving strong market penetration today for ground based turbine turbines as well.

In my graduate school and young professor days, we experimented with ways of making fully directionally solidified (i.e. columnar structure) castings of aluminum and steel. A graduate student at that time, G. Dixon Chandley went on to produce large steel castings with fully columnar structures for the US army. He then joined TRW Inc, developing in collaboration with Pratt and Whitney the first fully columnar, directionally solidified turbine blades.

Later, as Vice President of Technology of Hitchiner Mfg Company, Chandley invented a series of processes involving the filling of investment casting molds by applying a vacuum to the mold exterior. These processes permit filling investment molds without the need of ladling and pouring, and result in significant production economies. The "countergravity investment casting" processes share with other countergravity casting processes the important attribute of being able to fill molds in controlled fashion from the bottom up. Resulting in less turbulence and hence less danger of entrapping gas or oxides. For investment casting it also has the advantage of permitting much greater sprue loading and less wasted metal. The process is used today to produce automotive and other small castings in high volume and low cost.

Figure 18 illustrates the basic process. Shell ceramic molds are prepared with long snouts. In mold filling, the snout is dipped into a molten bath, and vacuum applied to the mold exterior, drawing liquid metal into the mold. The vacuum is retained until the casting and gates have solidified; it is then released, allowing the metal in the central sprue to return to the bath. The result is that the castings come out of the mold as individuals, without need for cutoff from the central sprue. One industrially important modification of this process permits casting under controlled atmosphere or in vacuum (with inert gas introduced at the end of melting to achieve the required pressure for mold filling). Another is centrifuging the solidifying casting with the sprue as axis. In this way, filling and soundness are improved, and metal can be released from the sprue while the castings are still molten.

Another example of the versatility of the shell investment casting process is the casting of art.

Richard (Dick) Polich was a graduate student in the foundry laboratory when Al Duca was engaged in the art casting research program described earlier. Dick went on to found an art foundry, now named Polich Tallix, Inc. His foundry has become an international leader in introducing advanced foundry and related metallurgical techniques to the art casting world. Central to his operation is the shell ceramic mold. His website is: polichtallix.com

Figures 19-21 show three examples of investment cast sculpture from Polich Tallix, Inc. Figure 19, entitled "Karma," was created by South Korean artist Do Ho Sum. The 27 foot high sculpture depicts a standing figure with a series of increasingly smaller crouching figures atop his shoulders. Each of the crouching figures masks the eyes of the figure below him. The message is clear: no one ever knows the future; no one ever knows how things will turn out.

Figure 20 depicts a Torosaurus. At 9 feet high, 21 feet long and weighing over 8,000 pounds this is a very large lost wax, ceramic shell casting…but there was no other way to maintain and reproduce the incredibly varied and difficult textures of the creature's body.

Figure 21 shows Maman, a giant female spider, 33 feet high by 34 feet long and 30 feet wide, by the French artist, Louise Bourgeois. This spectacular spider was dedicated to Bourgeois' mother. Six bronze casts of the spider were made and are in famous art museums in Spain, Korea, Canada and Japan.

Looking Ahead

I have not attempted in this lecture to summarize the many ways in which the computer has altered the foundry industry as a whole, including its processes. However, few foundry processes could operate efficiently, if at all, without modern computers and their accompanying instrumentation. The impact of computers and sophisticated electronics on processes will continue to grow. Modeling, for example, will go far beyond predicting mold filling and porosity formation, to include full microstructure details and mechanical properties. We can anticipate being able to perform non-contact measurement of chemical composition of molten metals. Perhaps we will see 3D printing of liquid or semi-solid metals.

There are very many foundry processes that have been developed in the 60 years of the existence of the Indian Institute of Foundrymen. Many of these have fallen by the wayside. Others are so new they have not yet been fully tested in the marketplace. Still others have achieved niche applications and are waiting in the wings, striving to achieve growth through technological improvement or a new market.

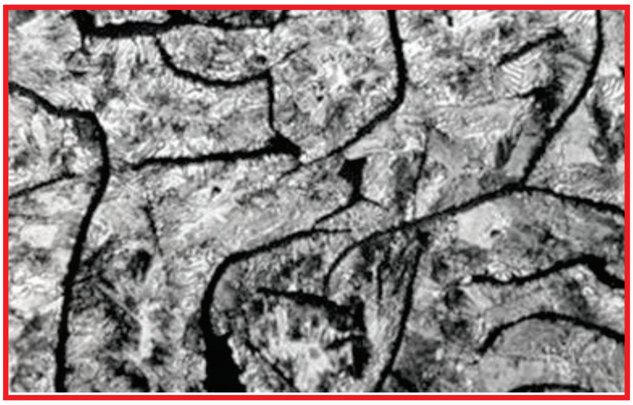
Metal infiltration to produce metal-ceramic composites is one of these processes. Figure 22 shows the first commercially produced metal matrix composite, The Toyota piston. Perhaps the greatest success to date is outside of what we normally think of as metal casting, in electronic substrates, Figure 23. Much interesting research is now underway on metal matrix composites with particulate or fiber sizes at the few microns or even nanometer scale. A leader in that research area is Andreas Mortensen, a former student in my laboratory, later MIT Professor and now professor at EPFL, Lausanne Switzerland. An interesting application of Professor Mortensen's research is very hard, practically scratch free gold for jewelry made by infiltrating gold into a very fine ceramic preform. This development is to be commercialized the Swiss watch making company Hublot.

Semi-solid technology is practiced to limited extent in several countries and continues to be widely researched. A variety of processes are employed. All rely on the fact vigorous agitation during the early stages of solidification produces a very fine grain size and that the structures so produced can be formed at fractions solid approaching 50%, Figure 24. An interesting extension of premium quality casting discussed earlier is "ablation casting," in which strong directional solidification is obtained be water jets ablating the mold and cooling the metal rapidly and directionally during solidification, Figure 25,

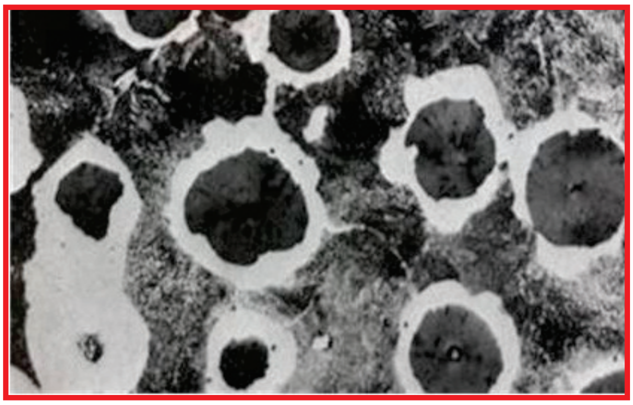
Perhaps out there in the future there will be a "game changer" that could be comparable, say, to ductile iron or shell investment casting. To think of a possibility, there is magnesium. Considering only thermodnamics and kinetics, magnesium in high production should be substantially cheaper than aluminum. Imagine development of a magnesium die casting alloys with mechanical properties and corrosion resistance that at least approach those of current aluminum alloys. Such a development, added to the lighter weight of magnesium and its probable lower cost of casting, would surely be such a game changer.

Let me close by describing one new process just entering production, the "SLIC" process developed by Metal Casting Technology, a joint venture of General Motors and Hitchiner Mfg. Co., Inc. Development of this process was undertaken with the aim of producing steel automotive castings in high volume and at low cost that would have many of the advantages normally associated with investment casting: dimensional accuracy, surface finish, integrity and thin sections. The process combines aspects of investment casting and lost foam casting. To avoid long heating times, the mold is heated from the inside out, Figure 26. The process starts with a foam polymer "tree" containing multiple foam patterns and coating this as in investment casting, to obtain a relatively thin shell. The tree is then backed by loose sand and heated internally until the pattern is fully removed and the inner section of the mold has been heated to the desired temperature for casting. Casting is then done by counter-gravity. The process has the potential to bring many of the advantages of investment casting to the automotive market along with substantially reduced cost and energy usage.

It is a great pleasure for me to be here to celebrate this important 60 year milestone of the Indian Institute of Foundrymen. May you continue to contribute to our field in important ways for many years to come.



Gray cast iron (left); ductile iron (right)



U. S. Production of gray, ductile and malleable Iron (tons) from 1950 to 2006, (Courtesy, American Foundry Society)

Foam Pegasus

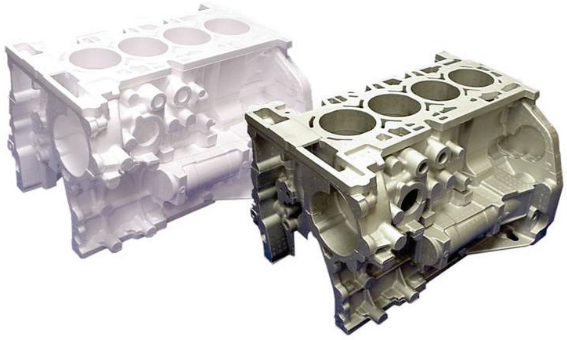
Foam Pattern for Pegasus

Pegasus Emerges

Pegasus being removed from the mold

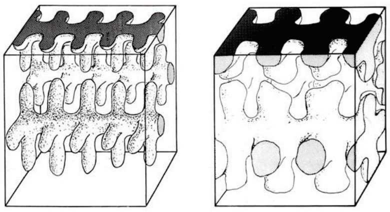
Pegasus

Completed Pegasus casting



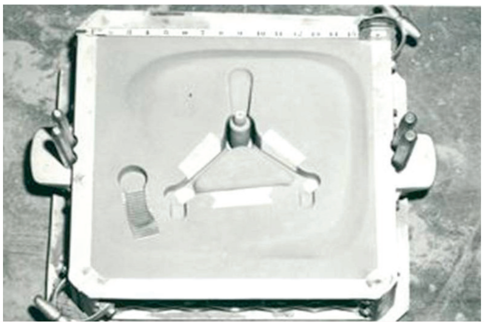
A foam pattern and finished engine block
(from “Lost Foam Casting Made Simple,”
Fred Sonnenberg Ed., American Foundry Society

Dendrite Structure



Dendrite structure: fine (left), coarse (right)

Grumman Bellcrank



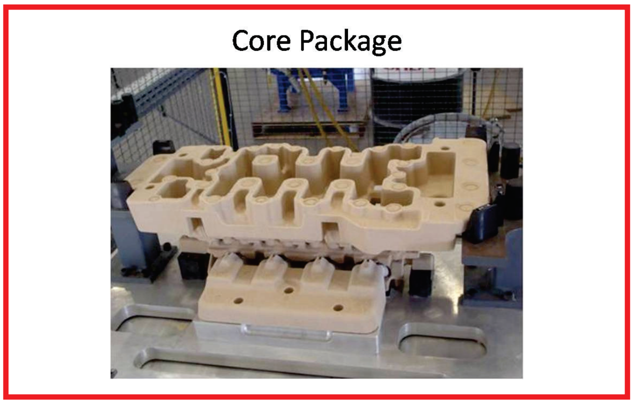
Drag half of mold for high strength “premium quality” casting, showing chill placement


Grumman Bellcrank

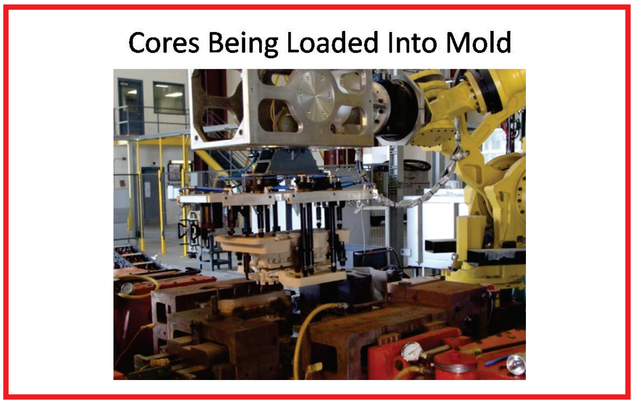
Premium quality casting


Prepared Metal Mold

Metal base plate for composite engine block mold
(Courtesy of General Motors, Powertrain)


Core Package

Sand cores for engine block mold,
(Courtesy of General Motors, Powertrain)


Cores Being Loaded Into Mold

Placing the core package,
(Courtesy of General Motors, Powertrain)

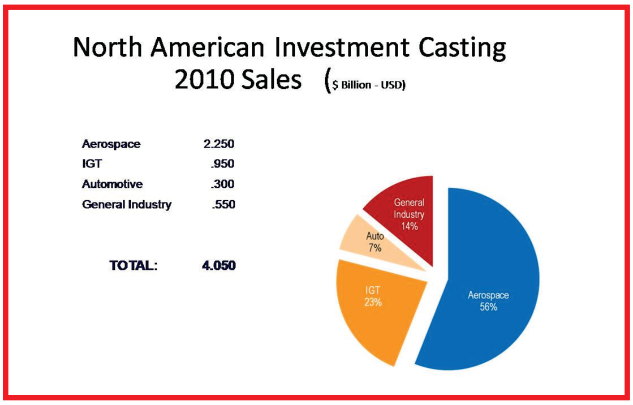

Casting Extracted From Mold

Removing the casting from the mold,
(Courtesy of General Motors, Powertrain)


Worldwide Investment Casting
2010 Sales (\$ Billion – USD)

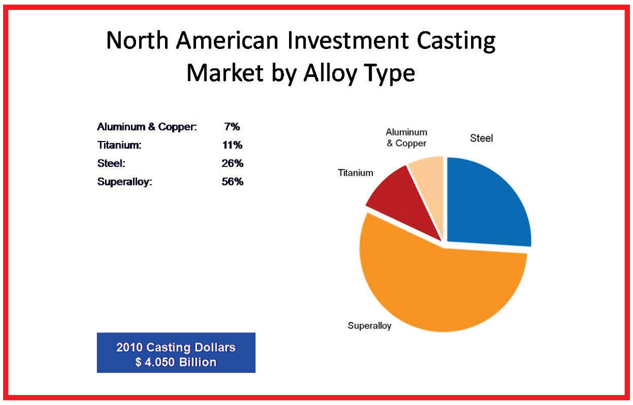
North America	4.050
Asia	3.350
Europe	2.430
South America	.100
Other	.100
Total	10.050

Worldwide investment casting sales,
(Courtesy of Investment Casting Institute)


North American Investment Casting
2010 Sales (\$ Billion - USD)

Aerospace	2.250
IGT	.950
Automotive	.300
General Industry	.550
TOTAL:	4.050

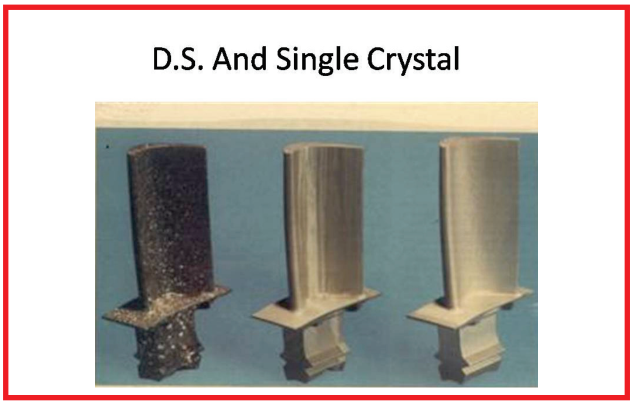
North American investment casting 2010 sales,
(Courtesy of Investment Casting Institute)


North American Investment Casting
Market by Alloy Type

Aluminum & Copper:	7%
Titanium:	11%
Steel:	26%
Superalloy:	56%

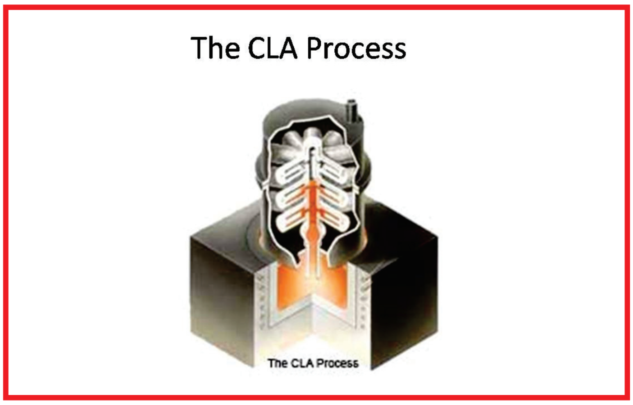
2010 Casting Dollars
\$ 4.050 Billion

North American investment casting sales by alloy type,
(Courtesy of Investment Casting Institute)



D.S. And Single Crystal

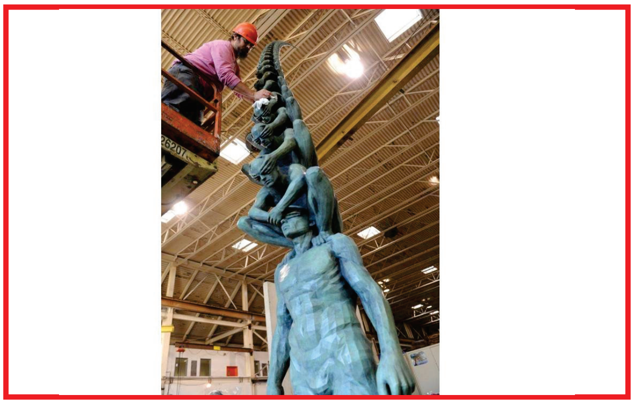
Directionally solidified ("D.S.") and "Single Crystal" turbine blades



The CLA Process

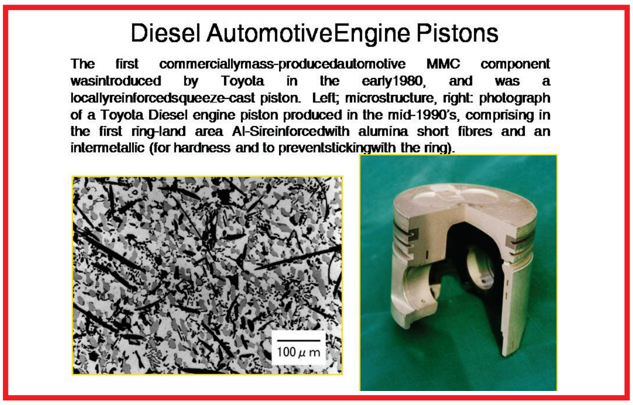
The "CLA" counter gravity investment casting process, (© Hitchiner Manufacturing Co., Inc.)

Investment cast sculpture, (Courtesy Pollich Tallix, Inc.)



Investment cast sculpture, (Courtesy Pollich Tallix, Inc.)

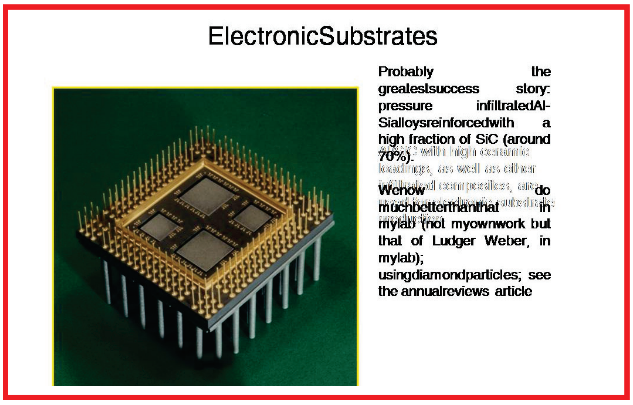
Investment cast sculpture, (Courtesy Pollich Tallix, Inc.)



Diesel AutomotiveEngine Pistons

The first commerciallymass-producedautomotive MMC component wasintroduced by Toyota in the early1980, and was a locallyreinforcedsqueeze-cast piston. Left; microstructure, right: photograph of a Toyota Diesel engine piston produced in the mid-1990's, comprising in the first ring-land area Al-Sireinforcedwith alumina short fibres and an intermetallic (for hardness and to preventstickingwith the ring).

Infiltrated metal matrix composite piston



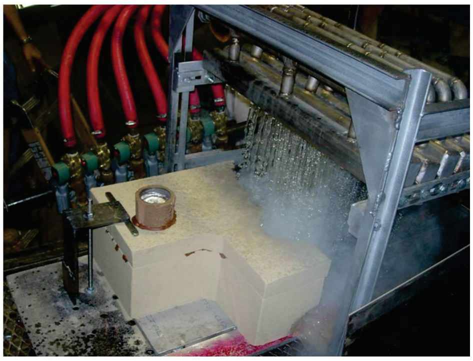
ElectronicSubstrates

Probably the greatestsuccess story: pressure infiltratedAl-Sialloysreinforcedwith a high fraction of SiC (around 70%). Wenow do muchbetterthanthat in mylab (not myownwork but that of Ludger Weber, in mylab); usingdiamondparticles; see the annualreviews article

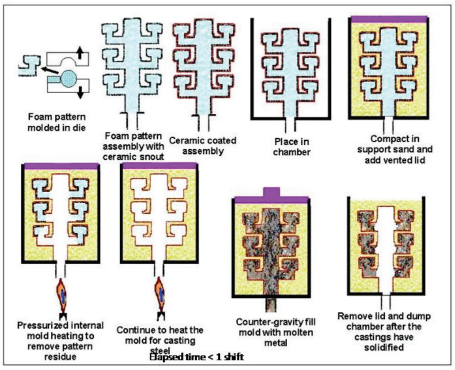
Al/SiC with high ceramic loadings, as well as other infiltrated composites, are used for electronic substrate production

Infiltrated electronic substrate

Demonstration of semi-solid alloy behavior



Ablation casting, (Courtesy of John Campbell, ALOTECH)



“SLIC,” a new casting process
(© Hitchiner Manufacturing Co., Inc.)